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Approximate entropy based on attempted steady isometric contractions with the ankle dorsal- and plantarflexors: Reliability and optimal sampling frequency

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ABSTRACT

The aim of this study was to (1) examine the test–retest reliability of approximate entropy (ApEn) calculated for torque time-series from attempted steady isometric contractions performed at two different days, and (2) examine the significance of the sampling frequency for the ApEn values. Eighteen healthy young subjects (13 ± 3 years, mean $\pm$ 1 S.D.) performed attempted steady isometric submaximal contractions with the ankle dorsal- and plantarflexors at two different days. Relative ($ICC_{3,1}$) and absolute (standard error of measurement [S.E.M.], and S.E.M.%) test–retest reliability was assessed for the ApEn values calculated for torque time-series down-sampled to 30 and 100 Hz, respectively. The relative reliability was generally moderate ($0.360 \le ICC_{3,1} \le 0.897$), with an absolute reliability (S.E.M.%) of 6–14%. The mean ApEn values varied considerably depending on the applied down-sampling frequency (5–200 Hz). When ApEn was used to quantify structure in the torque time-series, the relative and absolute reliability of steady isometric contractions with the ankle proved to be good in healthy young subjects. We propose that an optimal time-series down-sampling frequency exists for ApEn calculations, which will increase the sensitivity for biological system-changes, reduce adverse effects of random noise, and ensure that biological information in the signal is preserved. We recommend estimating this frequency using a variable high-pass filter-method for frequency analysis. Based on this method, the optimized time-series down-sampling frequency was around 30 Hz for the isometric contractions performed with the ankle in the present study.

1. Introduction

Traditionally, the amount of torque variability during attempted steady isometric contractions has been quantified by the standard deviation (S.D.) (Shinohara et al., 2008), and expresses a subject's level of selective motor control (Bandholm et al., 2008). However, the S.D. provides no information about the time-dependent structure in the torque time-series. Structure analysis contains information on the degree of regularity of the torque time-series, and expresses motor-system predictability. Force fluctuations, in healthy subjects, measured during specific submaximal isometric visuomotor tasks (isometric tremor) are determined by motor unit behaviour in terms of motor unit recruitment pattern and discharge rate, both of which are influenced by various mechanisms of peripheral and central origin (Deuschl et al., 1998; McAuley and Marsden, 2000; Baker and Baker, 2003; Taylor et al., 2003; Moritz et al., 2005). Furthermore, input to the motor neurons can be modified by e.g. training (Kornatz et al., 2005), functional neurosurgery (Kovacs et al., 2006), and neuropharmacology (Baker and Baker, 2003). Structure analysis of torque fluctuations in addition to amplitude analysis may therefore provide additional information on motor control strategies, and on effects of treatments aiming to improve the ability to perform goal-directed movements efficiently.

Torque time-series are, as the typical biological measurement, limited in the number of observations, and contain noise. One way to quantify the regularity of short time-series containing noise, is to calculate the approximate entropy (ApEn) (Pincus, 1991; Pincus, 1995). ApEn has been used to examine different biological systems (e.g. motor, organ, and endocrine systems), and system regularity has been found to change with age and in disease (Pincus et al., 1991; Vaillancourt et al., 2001; Vaillancourt and Newell, 2002; Georgoulis et al., 2006; Hong et al., 2006). ApEn quantifies the difference of the appearances of similar substructures (embedding vectors) in the time-series between two successive dimensions. High values of ApEn correspond to low system regularity and the other way around (Pincus, 1991). ApEn has been the preferred method to quantify motor-system regularity, when

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evaluated as torque time-series from attempted steady isometric contractions (Slifkin and Newell, 1999; Deutsch and Newell, 2004; Sosnoff et al., 2006, 2007; Sosnoff and Newell, 2006). Furthermore, ApEn values calculated for force time-series from attempted steady isometric index finger–thumb grip seem to correlate with the severity of Parkinson's disease (Vaillancourt et al., 2001). When SD analyses were applied to the same force time-series, no correlation was found (Vaillancourt et al., 2001). Therefore, ApEn analysis of torque time-series from attempted steady isometric contractions may be a potential suitable method to evaluate physical rehabilitation regimes, pharmacological interventions, or disease severity in neurology. However, prior to introducing this method in the clinical setting of neurology, the reliability of ApEn calculated for torque time-series from attempted steady isometric contractions performed at different days should be studied in a group of healthy subjects.

Originally, ApEn has been used to quantify the regularity of time-series from recordings of the time distance between heartbeats (Pincus et al., 1991), which is discrete by nature. When ApEn is applied to time-series from continuous biological signals, as the exerted torque, one has to consider the frequency content of significant biological information in relation to the sampling frequency. For embedding methods, including ApEn, bias associated with over-sampling exists (Fraser and Swinney, 1986; Cellucci et al., 2005). When calculating ApEn, the embedding vectors are constructed of successive observations in the time-series (Pincus, 1991), and therefore the absolute difference in amplitude between to successive observations is closely related to the sampling frequency. For the embedding vectors to reflect biological information, the absolute difference in amplitude between two successive observations should mainly be determined by changes in the biological system. That is, the general absolute change in amplitude should be larger than what is generated by the noise in the investigated time interval. Therefore, our hypothesis is that an optimal sampling frequency exists for the calculation of ApEn from time-series from continuous biological signals, e.g. examination of attempted steady isometric contractions. This sampling frequency is suggested to be the minimum sampling frequency that includes the highest measurable biological frequency.

The aim of this study was to (1) examine the test–retest reliability of ApEn calculated for torque time-series from attempted steady isometric contractions with the ankle dorsal- and plantarflexors performed at two different days, and (2) examine the significance of the sampling frequency for the ApEn values.

2. Methods

The study was designed as an inter-day reliability study with a mean ± 1 S.D. of 7.4 ± 0.8 days between test and retest visits.

2.1. Subjects

A total of 18 young healthy subjects (8 girls, 10 boys) with a mean ± 1 S.D. age of 13 ± 3 years, body mass of 45.4 ± 15.1 kg, and height of 155.0 ± 17.6 cm, participated. All subjects were physically active and reported no known neurological disorders. Written informed consent was obtained from their parents in accordance with the declaration of Helsinki. The Committee on Ethics in Science in Copenhagen approved the study (KF 02 323948).

2.2. Experimental arrangement

The subjects were seated in a custom-made rigid chair facing a computer screen (30 × 37 cm). Their non-dominant foot was placed in a device with a foot-stand connected to a Darcus strain-gauge dynamometer (Darcus, 1955). Foot dominance was determined according to Hoffman et al. (1998). The chair and foot-stand were adjustable, and joint angels of the hip, knee, and ankle were 90°, 150°, and 110°, respectively. The subjects were firmly strapped at the shoulders, hip, and thigh. The foot was strapped to the foot-stand at the instep of the foot and the first metatarsal head. Both hands were placed on the thighs (palms up) in order to prevent accessory trunk movement. The subjects were carefully instructed to exert force only across the ankle.

2.3. Experimental procedures

The subjects performed maximal dorsal- and plantarflexions in a randomized order after warm up and familiarization with the procedure. Three contractions, separated by 60 s pauses, were performed for each torque direction, and the subjects were instructed to gradually increase torque until the maximum was reached.

The submaximal contractions were performed at target torques (TT) of 0.1 and 0.3 Nm/kg body weight (dorsalflexion) and 0.3 and 0.5 Nm/kg body weight (plantarflexion). For details regarding the TT selection, see Bandholm et al. (2008). The subjects performed 10 practice trials, followed by 5 trials, which were recorded for analysis, for each TT. Each trial consisted of 13 s of contraction, followed by 60 s of pause. Visual feed-back of the TT was provided to the subjects as a black bold horizontal line in the centre of the computer screen (PicoScope 3000, Pico Technology Limited, Cambridgeshire, UK). The exerted torque was displayed as a blue bold horizontal line, which moved up and down synchronously with changes in exerted torque. The subjects were instructed to align the exerted torque to the TT, and then keep the exerted torque as steady as possible while aligned.

2.4. Data recording

All torque signals were low-pass filtered (cut-off frequency, f_c = 1 kHz), sampled at 1 kHz, A/D converted (16-bit, 6036E, National Instruments, Austin, TX, USA), and subsequently stored on a personal computer for further offline analysis (EMGworks acquisition 3.1, Delsys, Boston, MA, USA).

2.5. Offline data analysis

For the maximal contractions, torque values were calculated for a 1-s window using a moving average with a window overlap of 0.999 s. The maximal torque was the highest single 1-s value (for details, see Bandholm et al., 2008).

For the submaximal contractions, the initial four and the final 0.5 s of each trial were discarded prior to analysis to avoid initial transient data or premature cessation of torque production. Fast Fourier transformation and inverse fast Fourier transformation (sampling frequency = 1 kHz, block size = 8192 observations, frequency resolution = 0.122 Hz) was used as a variable high-pass filter-method for frequency analysis, to assess the highest measurable frequency in the torque time-series to be confidently considered biological. This criterion was set as the smallest Fourier high-pass filter-frequency that kept observations in the torque time-series within the range of ± the level of measurable noise. The level of measurable noise was determined as the 95% confidence interval (4 × S.D.) of the bandwidth of a constant-load sampling from the experimental set-up. The minimum sampling frequency for the subsequent ApEn calculations was calculated as two times the highest measurable biological frequency, according to the Nyquist rate (McClellan et al., 2003).

ApEn was calculated in order to examine motor-system regularity. The calculation of ApEn is given in great detail by